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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 270

THE MEASUREMENT OF PRESSURE THROUGH TUBES IN PRESSURE DISTRIBUTION TESTS

By PAUL E. HEMKE



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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length-----	l	meter-----	m	foot (or mile)-----	ft. (or mi.)
Time-----	t	second-----	sec	second (or hour)-----	sec. (or hr.)
Force-----	F	weight of one kilogram-----	kg	weight of one pound-----	lb.
Power-----	P	kg/m/sec-----		horsepower-----	HP.
Speed-----		km/hr-----		mi./hr-----	M. P. H.
		m/sec-----		ft./sec-----	f. p. s.

2. GENERAL SYMBOLS, ETC.

W , Weight, $=mg$	mk^2 , Moment of inertia (indicate axis of the radius of gyration, k , by proper subscript).
g , Standard acceleration of gravity $=9.80665$ m/sec. ² $=32.1740$ ft./sec. ²	S , Area.
m , Mass, $=\frac{W}{g}$	S_w , Wing area, etc.
ρ , Density (mass per unit volume).	G , Gap.
Standard density of dry air, 0.12497 (kg-m ⁻⁴ sec. ²) at 15° C and 760 mm $=0.002378$ (lb.-ft. ⁻⁴ sec. ²).	b , Span.
Specific weight of "standard" air, 1.2255 kg/m ³ $=0.07651$ lb./ft. ³	c , Chord length.
	b/c , Aspect ratio.
	f , Distance from $c. g.$ to elevator hinge.
	μ , Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V , True air speed.	γ , Dihedral angle.
q , Dynamic (or impact) pressure $=\frac{1}{2} \rho V^2$	$\rho \frac{VL}{\mu}$, Reynolds Number, where l is a linear dimension.
L , Lift, absolute coefficient $C_L = \frac{L}{qS}$	e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, 0° C: 255,000 and at 15° C., 230,000;
D , Drag, absolute coefficient $C_D = \frac{D}{qS}$	or for a model of 10 cm chord 40 m/sec, corresponding numbers are 299,000 and 270,000.
C , Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$	C_p , Center of pressure coefficient (ratio of distance of $C. P.$ from leading edge to chord length).
R , Resultant force. (Note that these coefficients are twice as large as the old coefficients L_C, D_C .)	β , Angle of stabilizer setting with reference to lower wing, $= (i_t - i_w)$.
i_w , Angle of setting of wings (relative to thrust line).	α , Angle of attack.
i_t , Angle of stabilizer setting with reference to thrust line.	ϵ , Angle of downwash.

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**THE MEASUREMENT OF PRESSURE THROUGH TUBES
IN PRESSURE DISTRIBUTION TESTS**

By **PAUL E. HEMKE**
Langley Memorial Aeronautical Laboratory

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NAVY BUILDING, WASHINGTON, D. C.

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By PAUL E. HEMKE

SUMMARY

The tests described in this report were made by the National Advisory Committee for Aeronautics to determine the error caused by using small tubes to connect orifices on the surface of aircraft to central pressure capsules in making pressure distribution tests.

Aluminum tubes of $\frac{3}{16}$ -inch inside diameter were used to determine this error. Lengths from 20 feet to 226 feet and pressures whose maxima varied from 2 inches to 140 inches of water were used. Single-pressure impulses for which the time of rise of pressure from zero to a maximum varied from 0.25 second to 3 seconds were investigated.

The results show that the pressure recorded at the capsule on the far end of the tube lags behind the pressure at the orifice end and experiences also a change in magnitude. For the values used in these tests the time lag and pressure change vary principally with the time of rise of pressure from zero to a maximum and the tube length. Curves are constructed showing the time lag and pressure change. Empirical formulas are also given for computing the time lag.

Analysis of pressure-distribution tests made on airplanes in flight shows that the recorded pressures are slightly higher than the pressures at the orifice and that the time lag is negligible. The apparent increase in pressure is usually within the experimental error, but in the case of the modern pursuit type of airplane the pressure increase may be 5 per cent. For pressure-distribution tests on airships the analysis shows that the time lag and pressure change may be neglected.

INTRODUCTION

The air pressure acting on an aircraft in flight is usually measured by providing an orifice at the point to be investigated and connecting this orifice to a manometer by means of a tube of comparatively small diameter. During steady rectilinear motions of the aircraft the pressure in the tube at the manometer end differs from the pressure at the orifice end only by the amount due to the differences in level of the two ends of the tube. This difference of pressure is usually quite small but may easily be computed.

While maneuvering the aircraft, however, the pressure at the orifice end of the tube changes more or less rapidly and a pressure wave is then propagated along the tube to the manometer. If now a second manometer is connected with the tube, at or very near the orifice, records of the pressure wave given by the two manometers show both a time displacement and a change of amplitude. This error in the reading of the manometer at the far end of the tube is due to the viscosity, elasticity, and mass of the air inclosed in the tube, to the inertia of the manometer parts, to the material of which the tube is made, and to the condition of the inside surface of the tube.

The error caused by the mass forces of the air inside the tube may be easily computed. This error can be avoided by using two tubes approximately equal in length and diameter to connect two orifices on opposite sides of a wing or fin to the same manometer. The mass forces due to the air inside the two tubes will be equal and will cancel each other in the difference of the two pressures. In the instruments now used the mass forces of the manometer

parts affect the readings to such a small extent that this error can be neglected. The material of which the tubes are made will not yield sufficiently, in the range of pressures encountered in aeronautical research, to cause any appreciable error unless the tubes are made of rubber.

The error due to the viscosity and elasticity of the air depends chiefly on the length and diameter of the tube and the time rate of change of pressure at the orifice. This error has not yet been computed, and extensive analysis has shown that the phenomenon giving rise to it is quite complicated. It is likely that our present knowledge of the mechanism of air flow very near solid boundaries must be considerably extended before this error can be calculated.

The Aeronautical Research Committee (British) has published a preliminary report describing experiments dealing with the transmission of air waves through pipes (Reference 1). A test to determine the effect of tube length upon the recorded pressure has been made on an airplane in flight (Reference 2). The tests described in this report were made concurrently with and independently of the experiments made by the British (Reference 1) and previous to the flight tests described in Reference 2. Two series of experiments were made as follows:

(a) *Experiments with tubes of very small diameter using pressures changing periodically:*

These tests were undertaken to determine the suitability of tubes of very small diameter for transmitting pressures acting at various points on the surface of an aircraft. Both time displacement and change in amplitude of a pressure wave as recorded by two manometers, one at the near or orifice end of the tube and the other at the far end, were studied. Frequencies and amplitudes were used which would permit comparison with a previously derived theoretical formula due to Rayleigh (Reference 3).

The experiments with these very small tubes soon showed that condensation on the inner surface of the tubes due to atmospheric conditions and other slight obstructions in the tubes would very seriously affect the correct interpretation of the results obtained.

(b) *Experiments with larger tubes using single pressure waves:*

In this series of tests aluminum tubes of $\frac{3}{16}$ -inch inside diameter were used. Single-pressure impulses of various rates of pressure rise and of various amplitudes were used exclusively. Time displacement and change in amplitude, as previously described, were investigated. Results could be reproduced under varying atmospheric conditions with sufficient accuracy to warrant continuing the tests.

It is not claimed that the empirical information obtained in these tests is an exhaustive study of the transmission of pressure waves through tubes. The tests reproduced conditions as they exist in what is now standard practice at the Langley Memorial Aeronautical Laboratory in making pressure distribution tests—i. e., using aluminum tubes of $\frac{3}{16}$ -inch inside diameter to connect orifices to standard manometer capsules. The information obtained is useful to the flight-research engineer in enabling him to foresee when large errors are likely to be encountered and what the approximate errors actually are in tests with known tube lengths and known rates of pressure rise.

METHODS AND APPARATUS

(a) *Experiments with pressures changing periodically:*

The first series of experiments were made with round brass tubes, 0.040 and 0.048 inch inside diameter. The lengths of the tubes varied from 15 to 35 feet.

As shown in Figure 2, the two ends of each tube used were connected to pressure-measuring capsules similar to those described in N. A. C. A. Technical Note No. 233 (Reference 4). These capsules are closed by thin metallic diaphragms, deflecting elastically under the action of a pressure difference on the two sides of the diaphragm. These deflections are transferred mechanically to a small mirror, which reflects a light beam to a sensitive photographic film. In this way a record is created on the film indicating the pressure at each moment of the interval. One film was exposed to the light beams of two such capsules. Figure 1 represents a record so obtained. The film moved from right to left at uniform speed, so that the length of a horizontal line represents a time. The two horizontal lines AA' and BB' represent the zero pressure readings for

the two capsules. Two curves M and M' indicate the deflections of the diaphragms, and points of the two curves lying on the same vertical line give the pressures at the two ends of the tube at the same moment.

At one end of the tube a periodically changing pressure was created by means of a "pressure oscillator," diagrammatically represented in Figure 2. At the other end of the tube the pressure changed periodically also, but pressures at the two ends did not necessarily agree. The photo-

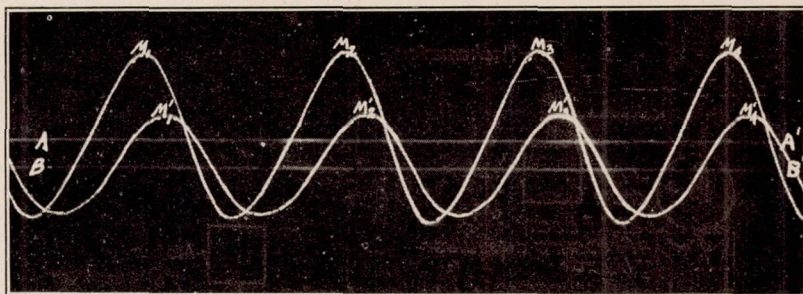


FIG. 1.—A photographic record from the tests with very small tubes using pressures changing periodically

graphic records obtained give the differences of pressures at the two ends, and thus furnish experimental data for studying the physical laws governing the magnitude of such pressure differences.

The pressure oscillator shown in Figure 2 consisted of a cylinder in which a piston was made to reciprocate by an eccentric cam. This motion was so regulated that a maximum air pressure of about $1\frac{1}{2}$ inches of water was reached. The pressure wave traversing the tube H leading from the cylinder was recorded at a point near the origin by means of a pressure-recording

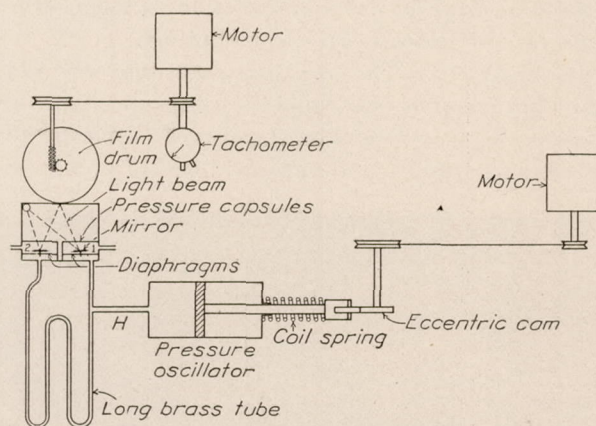


FIG. 2.—Apparatus used in tests with tube of very small diameter, pressure changing periodically

device or "capsule" 1, which was attached to the tube by a tee joint. After traversing the full length of the tube the pressure was recorded on capsule 2.

(b) *Tests with single-pressure waves:*

The second series of tests were made with aluminum tubes of $\frac{3}{16}$ -inch internal diameter. Lengths from 20 to 226 feet, and pressures whose maxima varied from 2 to 140 inches of water, were used. The time of rise of pressure from zero to a maximum varied from 0.25 to 3 seconds.

The piston type of pressure oscillator was not well adapted for securing a wide pressure range. Accordingly, a valve arrangement shown in the sketch at the lower right-hand corner of Figure 3 was substituted.

A tank of large volume containing air at a known, constant pressure was connected by a pipe to the pressure-control valve. Air from the tank flowed into the chamber A and into the tubes when the poppet valve B opened. This made the pressure in the tubes equal to that in

the tank. At any desired time thereafter valve B was quickly closed and valve C opened. The air in the tubes was thereby again reduced to atmospheric pressure through the vent D. By altering the shapes and the relative settings of the cams, various kinds of pressure variations were obtained. A wider latitude for variation of pressure maxima and rate of change of pressure was allowed with this system than with the piston type of oscillator.

In this manner a single pressure wave was propagated through the tube. It was recorded on the film by capsule 1 when it entered the tube and by capsule 2 when it reached the end.

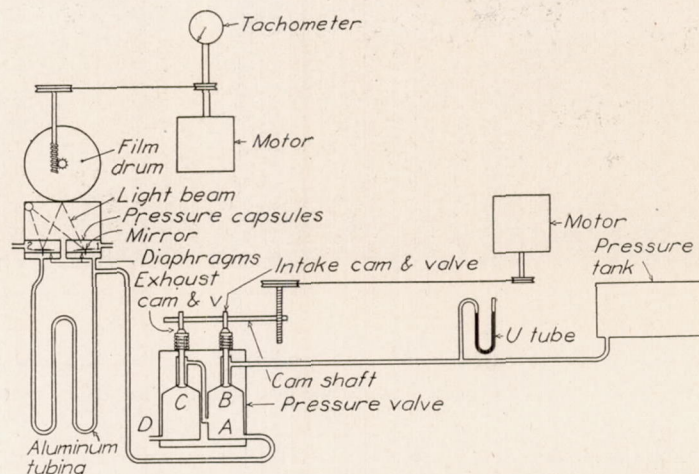


FIG. 3.—Apparatus used in tests with tubes of $\frac{1}{8}$ inch inside diameter single pressure waves

The tachometer gave the film drum speed and the calibration of the capsules gave the pressures obtained. By starting the film drum at different positions a mean of four readings at the same pressure and for the same rate of pressure rise was obtained.

Figure 4 shows a typical record. The zero pressure lines AA' and BB' were obtained by making an exposure of the photographic film when both capsules registered atmospheric pressure. This is called the zero pressure in the text and on the curves. In order to get full-scale deflections of the capsules, the zero pressure line BB' for capsule 2 was placed at the top of the film and the

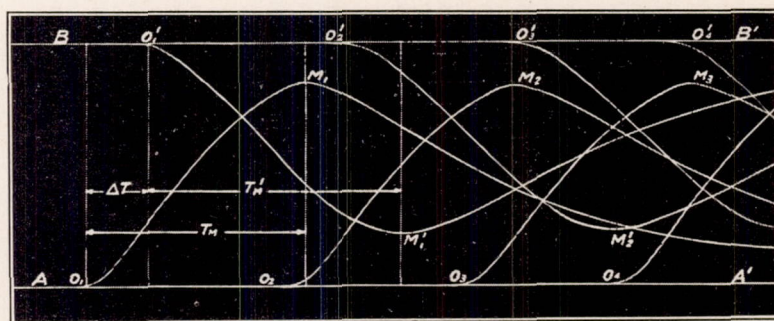


FIG. 4.—A photographic record from the tests with tubes of $\frac{1}{8}$ inch inside diameter using single pressure waves

records as obtained from this capsule were $O_1' M_1', O_2' M_2',$ etc. AA' similarly represents the zero line for capsule 1 and $O_1 M_1$ and $O_2 M_2,$ etc., the records of this capsule. Points $O_1, O_2, \dots, M_1, M_2,$ etc. were marked on the film with great care. Very fine lines were drawn by means of a stylus through the points thus located. These lines are perpendicular to AA' and BB' in direction. The time displacement of the pressure wave was studied by measuring the following quantities:

- (1) T_M , the time of rise of pressure, from zero to a maximum, of the pressure wave at the orifice.

- (2) T_M' , the time of rise of pressure, from zero to a maximum, of the pressure wave after it had traversed the tube.
- (3) ΔT , the time required for the front of the pressure wave to traverse the tube.

The time displacement, T_L , of the peaks of the two waves is of interest and was determined in each case by means of the equation $T_L = T_M' + \Delta T - T_M$. This quantity is called time lag in the report.

Figure 5 shows a record where the loss in pressure as well as the time displacement were greater, due to a more rapid rate of pressure rise.

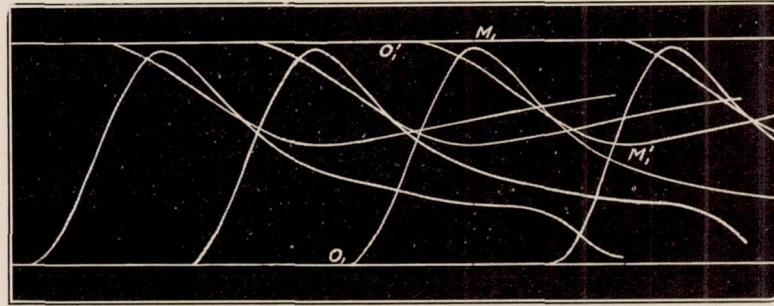


FIG. 5.—A photographic record from the tests with tubes of $\frac{1}{8}$ inch inside diameter showing a rapid rate of pressure rise

RESULTS

(a) Experiments with pressures changing periodically:

The tests with sine waves show a regular time lag. In Figure 6 the observed time lag is plotted in seconds per foot as ordinate against the frequency of oscillation per second as abscissa.

Lamb has published (Reference 3) a formula derived by Rayleigh from theory only. It enables us to find the time lag for small oscillations and small tubes in the form,

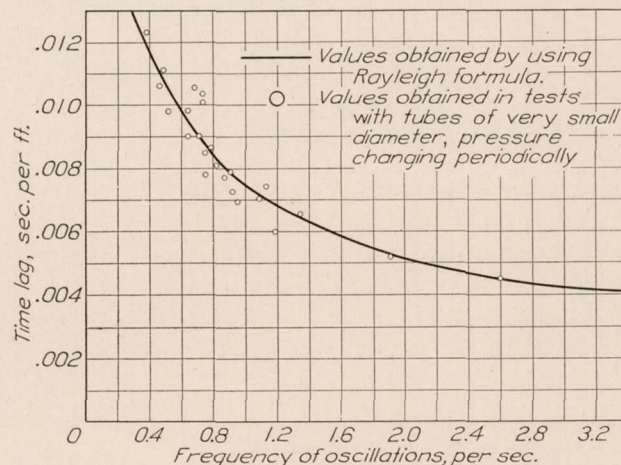


FIG. 6.—Comparison of results obtained in tests using tubes of very small diameter, pressure changing periodically with Rayleigh formula

$$T_L = \frac{r}{2} \sqrt{\frac{2\pi p_o N}{\mu}} \quad (1)$$

where

T_L = time lag

r = internal radius of tube

p_o = zero pressure

N = frequency of oscillation

μ = coefficient of viscosity of air.

The value obtained from the lag when the Rayleigh formula is used is plotted in Figure 6, together with the values found in the experiments.

(b) Experiments with single pressure waves:

Analysis of the results showed that T_M , T_M' and ΔT (fig. 4) could be readily expressed by means of empirical formulas. These formulas, which hold in the range of values used for tube length, rate of pressure rise and maximum pressure, are as follows:

$$T_M' = k T_M^m$$

$$k = 1 + (P^{4.84} \times 10^{-15}) L^{4.94} - .0542P + .000227P^2 \quad (2)$$

$$m = 1 - .000796 L - .000393 P$$

$$T = k_1 T_M^{m_1}$$

$$k_1 = (9.50 - .016P) \times 10^{-4} L^{1.1} \quad (3)$$

$$m_1 = (1.30 - .00311P) \times 10^{-3} L$$

From these the time lag T_L was found by means of

$$T_L = \Delta T + T_M' - T_M \quad (4)$$

Figures 7 and 8 are curves of T_L and T_M' plotted against T_M for the shortest and longest tube lengths used. In Figure 7 the maximum pressure is 5 inches of water, in Figure 8 it is 140 inches of water.

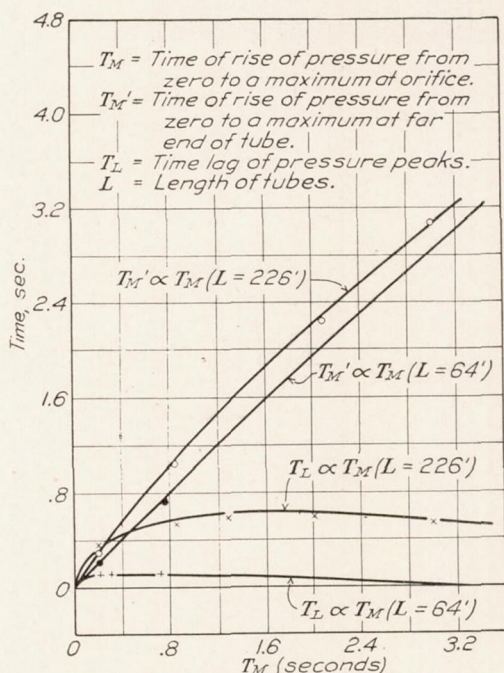


FIG. 7.—Maximum pressure 5 inches of water. Aluminum tubes $\frac{1}{8}$ inch inside diameter

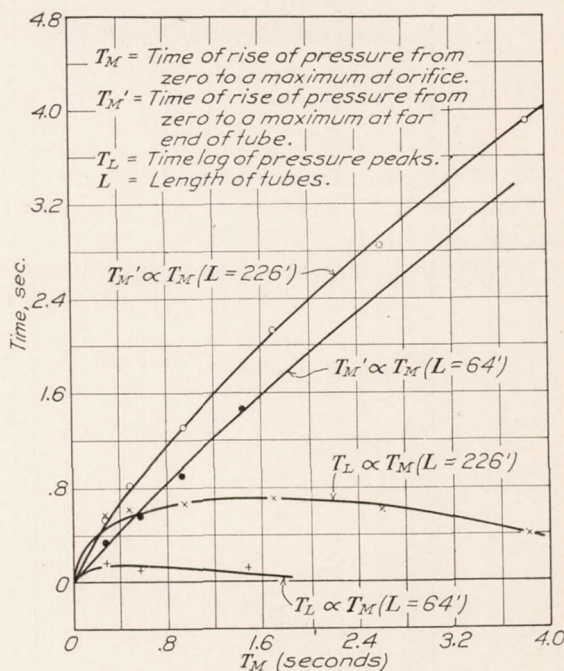


FIG. 8.—Maximum pressure 140 inches of water. Aluminum tubes $\frac{1}{8}$ inch inside diameter

Effect of change of maximum pressure and tube length on time lag of pressure peaks and time of use of pressure at end of tubes.

The maximum time lag or time displacement of pressure peaks is 0.7 second and occurs when $T_M' = 1.9$ seconds, the pressure maximum being 140 inches of water. This maximum time lag, however, occurs for only the longest tube. The time lag is affected principally by the tube length, the increased pressure not having a very large effect. This small change due to the increased pressure is not surprising inasmuch as the pressure range extends only from 1 to 1.34 atmospheres.

Analysis of the results revealed no simple formulas for the pressure loss or change in amplitude due to the frictional and other losses in the tubes. Figures 9, 10, 11, and 12 show in graphical form the pressure loss for maximum pressures of 2, 10, 60, and 140 inches of water as plotted against tube length. The pressure loss is expressed as a per cent of loss of the pressure at the orifice. Several values of the time required for the pressure to rise from zero to a maximum are shown for each maximum pressure.

In the tests with long tubes and slow rates of pressure rise the pressure maximum at the end of the tube proved to be smaller than the pressure maximum at the orifice end. For the shorter tubes and the more rapid rates of pressure rise the reverse was true, the phenomenon being very similar to that known as "water hammer."

At the time of writing no analytical formula has been discovered which may be used to compute the change of amplitude and time lag. The Rayleigh formula previously cited does not give results agreeing with the results obtained in the second series of experiments. The British tests which were restricted to pressures whose maximum value did not exceed 0.59 inch (15 mm.) of water did not yield results agreeing with analytical formulas.

APPROXIMATE ERRORS DUE TO THE USE OF TUBES FOR MEASURING AIR PRESSURES ON AIRCRAFT IN FLIGHT

The discussion will be limited to those errors caused by the viscosity and elasticity of the air. The results obtained in the laboratory tests with aluminum tubes of $\frac{3}{16}$ -inch internal diameter are used to determine the approximate error in the manometer readings. These results include the error due to the inertia of the manometer parts and the error caused by the slight expansion of the tubes.

A comparison was first made with a flight test (Reference 2) where a direct measurement had been made of the error due to the use of tubes of different length leading from an orifice on the surface of the wing of a JNS-1 airplane to the manometers. The rate of pressure rise was comparatively slow and consequently no appreciable errors could be expected. The most rapid rate of observed pressure rise was 4 inches of water in 1 second. The tube length used was 25 feet. The empirical formula for time lag gives a very small value which may be neglected. Figures 9 and 10 show that the change in pressure is negligible. The flight tests verified this as no measurable errors were observed.

The determination of the approximate error in flight tests which have been made previously is complicated by the fact that it is common practice to connect two orifices on opposite sides of a wing, fin, or tail surface to the two sides of a manometer and in this way measure the resultant pressure. The error is then a resultant of the errors of the two sets of orifices and tubes. Flight tests made recently with a VE-7 airplane (Reference 5) were used in determining the approximate errors. R. A. F. 15 wing sections are used on this airplane and pressure distribution tests (Reference 6) on a biplane model with this wing section gave some information about the pressures on the upper and lower surfaces of the wing. These tests showed that the average value of the magnitude of the maximum pressures on the lower surface was 75 per cent of the maximum resultant pressure and on the upper surface 25 per cent of the maximum resultant pressure while the angle of attack was being changed from that of zero lift to maximum lift. The maneuver in which large pressures occur and in which the rate of pressure rise is also fairly rapid is a pull up at high speed. As the principal changes in the aerodynamic forces in this maneuver are those due to the change in angle of attack it was assumed that the maximum pressures on the lower and upper surfaces are 75 per cent and 25 per cent, respectively, of the maximum resultant pressure. With this assumption the maximum errors found for the pressures on the upper wing of the VE-7 in a pull up at 126 M. P. H. were pressure gains of 1 per cent and time lags of 0.025 second. For pressures on the tail surface where the tubes were longer the pressure gain did not exceed 1.5 per cent and the time lag 0.03 second. The longest tube used was about 20 feet in length, the maximum pressure was 30 inches of water, and the minimum value of the recorded time of rise of pressure ($T_{M'}$) was 0.50 second. In flight tests now being made with a PW-9 airplane the maximum pressures will be higher and the values of $T_{M'}$ will probably be less than those in the VE-7 tests. Tube lengths do not exceed 25 feet and from the curves in Figures 9, 10, 11, 12 it is seen that the maximum error is a pressure gain of 3 per cent (approximately) if $T_{M'}$ is not less than 0.5 second. If $T_{M'}$ should be as low as 0.25 second the maximum pressure gain would be approximately 8 per cent. This comparatively large pressure gain would occur only for the smaller pressures, so that the total wing load would not be recorded 8 per cent higher than it really is.

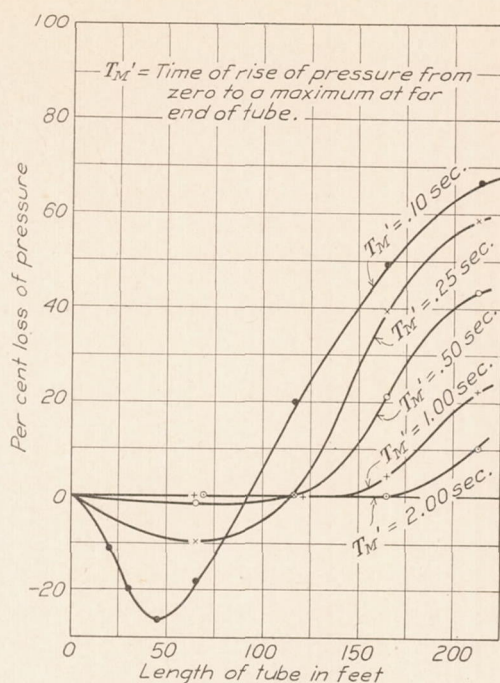


FIG. 9.—Maximum pressure 2 inches of water. Aluminum tubes $\frac{1}{8}$ inch inside diameter

Effect of the tube length and rate of pressure rise on the maximum pressure at the far end of the tube for various maximum pressures at the orifice end of the tube.

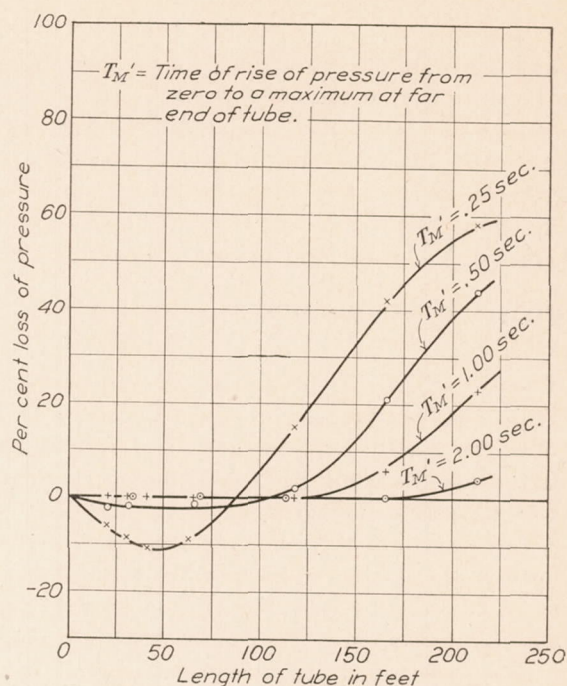


FIG. 10.—Maximum pressure 10 inches of water. Aluminum tubes $\frac{1}{8}$ inch inside diameter

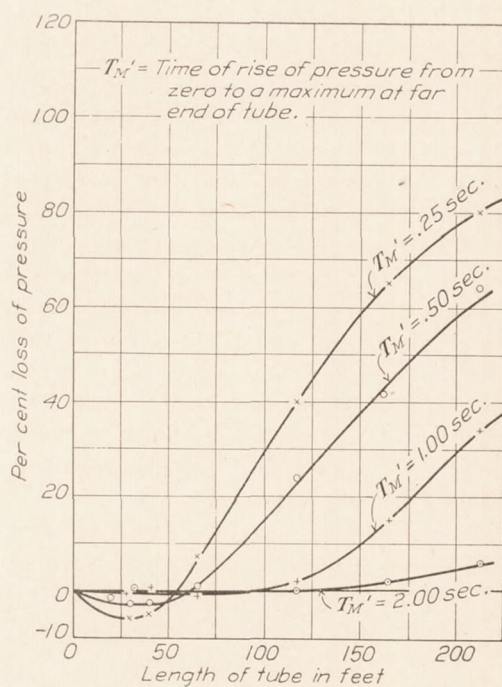


FIG. 11.—Maximum pressure 60 inches of water. Aluminum tubes $\frac{1}{8}$ inch inside diameter

Effect of the tube length and rate of pressure rise on the maximum pressure at the far end of the tube for various maximum pressures at the orifice end of the tube.

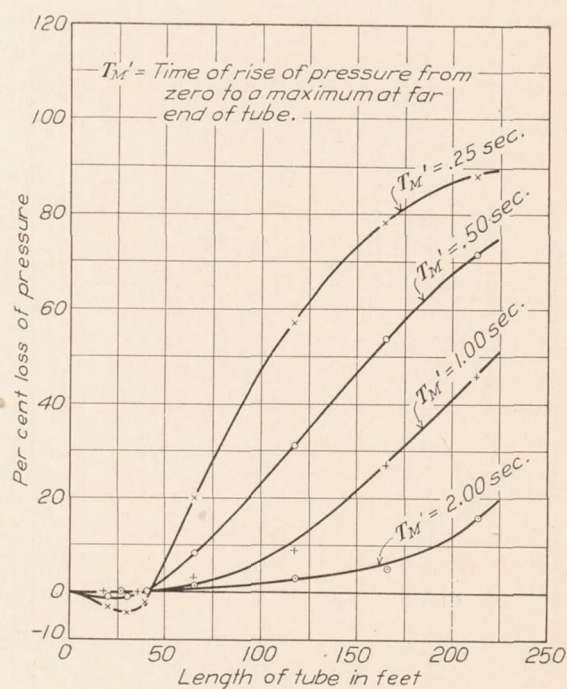


FIG. 12.—Maximum pressure 140 inches of water. Aluminum tubes $\frac{1}{8}$ inch inside diameter

It appears then that even for modern high-speed airplanes the pressure losses are nil when tubes under 40 feet in length are used. The pressure errors are of such a nature that the designer using the records of pressure distribution tests without making corrections for possible tube errors is on the safe side.

In pressure distribution tests on airships in maneuvers the tubes are longer, the maximum pressures are smaller, and the rates of pressure rise much less than in tests with airplanes. In flight tests made recently on the airship U. S. S. *Los Angeles*, the most rapid rise of pressure was from zero to 3 inches of water in 16 seconds in a tube 100 feet in length. From the curves of pressure loss it is seen that this maneuver is so slow that the conditions may be considered as steady with a negligible pressure error and time lag.

CONCLUSIONS

These tests indicate that the pressure distribution measurements previously made and those now being made in flight research on aircraft, using aluminum tubes ($\frac{3}{16}$ -inch inside diameter) for connecting pressure capsules to orifices are on the whole quite accurate.

The error caused by the viscosity and elasticity of the air in the tubes is, for conditions approximating those of actual flight of airplanes, such as to make the recorded pressures higher than the actual pressures. For the types which have already been tested this apparent pressure gain is about 1 per cent in magnitude and is less than the experimental errors. For an airplane of the modern pursuit type the apparent pressure gain may reach 5 per cent. In pressure distribution tests on airships the time of rise of pressure is so slow that, even with the longer tubes necessary, the pressure loss or gain is negligible.

The magnitude of the time lag is so small that it does not affect the pressure distribution measurements made in flight research on aircraft.

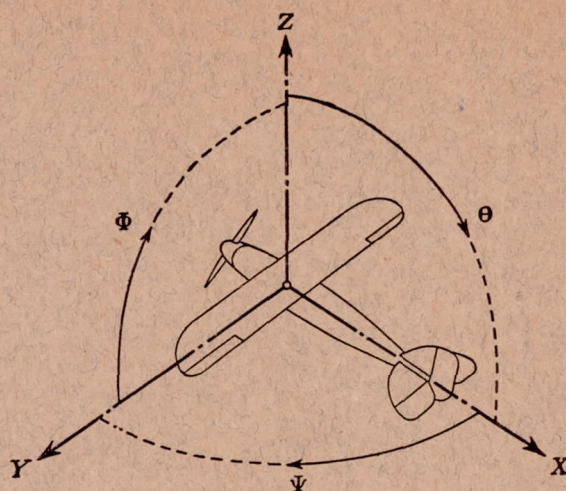
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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *February 23, 1927.*

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Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Sym- bol		Designa- tion	Sym- bol	Positive direction	Designa- tion	Sym- bol	Linear (compo- nent along axis)	Angular
Longitudinal---	X	X	rolling-----	L	Y → Z	roll-----	Φ	u	p
Lateral-----	Y	Y	pitching-----	M	Z → X	pitch-----	Θ	v	q
Normal-----	Z	Z	yawing-----	N	X → Y	yaw-----	Ψ	w	r

Absolute coefficients of moment

$$C_L = \frac{L}{q b S} \quad C_M = \frac{M}{q c S} \quad C_N = \frac{N}{q f S}$$

Angle of set of control surface (relative to neu-
tral position), δ . (Indicate surface by proper
subscript.)

4. PROPELLER SYMBOLS

D , Diameter.
 p_e , Effective pitch
 p_g , Mean geometric pitch.
 p_s , Standard pitch.
 p_v , Zero thrust.
 p_a , Zero torque.
 p/D , Pitch ratio.
 V' , Inflow velocity.
 V_s , Slip stream velocity.

T , Thrust.
 Q , Torque.
 P , Power.

(If "coefficients" are introduced all
units used must be consistent.)

η , Efficiency = $T V/P$.
 n , Revolutions per sec., r. p. s.
 N , Revolutions per minute., R. P. M.
 Φ , Effective helix angle = $\tan^{-1} \left(\frac{V}{2\pi r n} \right)$

5. NUMERICAL RELATIONS

1 HP = 76.04 kg/m/sec. = 550 lb./ft./sec.
 1 kg/m/sec. = 0.01315 HP.
 1 mi./hr. = 0.44704 m/sec.
 1 m/sec. = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.
 1 kg = 2.2046224 lb.
 1 mi. = 1609.35 m = 5280 ft.
 1 m = 3.2808333 ft.